Statement	Parameter	Default	Units
IMPACT	JPX.MIN	0.0	A/cm^2
IMPACT	JPY.MIN	0.0	A/cm^2
IMPACT	JPZ.MIN	0.0	A/cm^2

Table 3-94 Parameters for Specifying Minimum Current Values

3.6.5 Geiger Mode Simulation

Geiger mode simulation is the calculation of the single photon, single electron, or single hole probability of of avalanche breakdown usually in devices that are cooled sufficiently to neglect thermal generation of carriers. These calculations are done using line integrals suggested by McIntyre [179] of ionization rates along paths of steepest potential gradient. These calculations are done as a post-processing step after convergence is obtained without any impact ionization or thermal generation models being turned on.

To enable the post processing, you should specify GEIGER on the MODELS statement. The next three different calculations can be done. First, you can probe the value of the probability of avalanche due to introduction of an electron, hole, or electron-hole pair by specifying PE.AVALANCE, PH.AVALANCHE, or PP.AVALANCE on the PROBE statement. This should be accompanied by the location of the probe using the X and Y parameters of the PROBE statement. Second, if you specify a value for the FILENAME parameter of the PROBE statement, the line integral through the specified point will also be outputted to the specified file. Finally, once GEIGER is specified on the MODELS statement, all structure files saved thereafter will contain the spatial distribution of the probabilities of electron, hole, and pair generated avalanche breakdown.

3.6.6 Band-to-Band Tunneling

Standard Models

If a sufficiently high electric field exists within a device local band bending may be sufficient to allow electrons to tunnel, by internal field emission, from the valence band into the conduction band. An additional electron is therefore generated in the conduction band and a hole in the valence band. This generation mechanism is implemented into the right-hand side of the continuity equations. The tunneling generation rate is [112,113,114,137] as:

$$G_{BBT} = D \ \mathtt{BB.A} \ E^{\mathtt{BB.GAMMA}} exp\left(-\frac{\mathtt{BB.B}}{E}\right) \tag{3-429}$$

where E is the magnitude of the electric field, D is a statistical factor, and BB.A, BB.B, and BB.GAMMA are user-definable parameters. In ATLAS, there are three different sets of values that may be applied to the model parameters.

The model parameters can be set to the standard model [112] by specifying BBT.STD on the MODELS statement. The parameter defaults for the standard model are as follows:

BB.A = 9.6615e18 cm^{-1} V^{-2} s^{-1} BB.B= 3.0e7 V/cm BB.GAMMA= 2.0

The model parameters may also be set to the Klaassen Model [112,137,113] by specifying `BBT.KL` on the `MODELS` statement. The parameter defaults for the Klaassen model are as follows:

`BB.A` = 4.00e14 $cm^{-1/2}$ $V^{-5/2}$ s^{-1} `BB.B` = 1.9e7 V/cm `BB.GAMMA`= 2.5

In application, use the standard model with direct transitions while using the Klaassen model with indirect transitions.

Another modification allows these model parameters to be calculated from the first principles by specifying the `AUTOBBT` parameter in the `MODELS` statement. In this case, the parameters are calculated according to

$$\mathrm{BB.A} = \frac{q^2\sqrt{(2\times\ \mathrm{MASS.TUNNEL}\ m_0)}}{h^2\sqrt{\mathrm{EG300}}} \tag{3-430}$$

$$\mathrm{BB.B} = \frac{\pi^2\ \mathrm{EG300}^{\frac{3}{2}}\sqrt{\dfrac{\mathrm{MASS.TUNNEL}\ m_0}{2}}}{qh} \tag{3-431}$$

$$\mathrm{BB.GAMMA} = 2 \tag{3-432}$$

where q is the electronic charge, h is Planck's constant, E_g is the energy bandgap, m_0 is the rest mass of an electron and `MASS.TUNNEL` is the effective mass. The parameter `MASS.TUNNEL` may be set on the `MODELS` statement and the bandgap at 300K, EG300, is defined on the `MATERIAL` statement.

An alternative expression to Equation 3-503 for `BB.B` is used if the flag `AUTOBBT2` is set on the `MODELS` statement. This is

$$\mathrm{BB.B} = \frac{8\pi\sqrt{2m_o\mathrm{MASS.TUNNEL}}\ \mathrm{EG300}^{3/2}}{3qh} \tag{3-433}$$

The value of `BB.A` is the same for the `AUTOBBT` parameter as with the `AUTOBBT2` parameter.

The default value of the statistical factor D is 1. This factor can be calculated as suggested by Hurkx et al [112]:

$$D = \frac{n_{ie}^2 - np}{(n+n_{ie})(p+n_{ie})} \tag{3-434}$$

To enable this modification, specify `BBT.HURKX` in the `MODELS` statement. If `BBT.DEHURKX` is specified in the `MODELS` statement, then D will be set to 0 if

$$D = \begin{cases} 0 & \text{if } \nabla\phi n\cdot E > 0 \ \text{ and } \ \nabla\phi p\cdot E > 0 \\ \dfrac{n_{ie}^2 - np}{(n+n_{ie})(p+n_{ie})} & \text{otherwise} \end{cases} \tag{3-435}$$

If BBT.DJHURKX is specified in the MODELS statement, then D will be set to 1 if

$$D = \begin{cases} 1 & j_n > 1 \times 10^{-3} q n_{ie} \mathrm{VSATN} \text{ and } \\ & j_p > 1 \times 10^{-3} q n_{ie} \mathrm{VSATP} \\ \dfrac{n_{ie}^2 - np}{(n+n_{ie})(p+n_{ie})} & \text{otherwise} \end{cases} \tag{3-436}$$

If the BBT.ALPHA parameter is specified in the MATERIAL statement, then the statistical factor will be given by

$$D = \frac{n_{ie} - np}{(n+n_{ie})(p+n_{ie})} \qquad (1 - |\mathrm{BBT.ALPHA}|) - \mathrm{BBT.ALPHA} \tag{3-437}$$

where

- BBT.ALPHA=0 corresponds to the original Hurkx model,
- BBT.ALPHA=1 corresponds to recombination only, and
- BBT.ALPHA=-1 corresponds to generation only.

If BBT.SHURKX is specified in the MODELS statement, then the statistical factor will be taken from Schenk et al [240].

Table 3-95 User-Definable Parameters in the Band-to-Band Tunneling Model

Statement	Parameter	Default	Units
MODELS	BBT.ALPHA	0	
MODELS	BB.A	4.0×10^{14}	$cm^{-1/2}\ V^{-5/2}\ s^{-1}$
MODELS	BB.B	1.9×10^{7}	V/cm
MODELS	BB.GAMMA	2.5	

Schenk Band to Band Tunneling Model

A comprehensive study of band-to-band tunneling was carried out by Schenk [240]. A rigorous theory was developed and then an approximate result suitable for use in device simulations was derived. The result shows that phonon assisted band-to-band tunneling rate is generally dominant compared to the band-to-band tunneling that doesn't involve a phonon scattering event. The direct band-to-band tunneling is thus neglected. The model also assumes that the electric field is constant over the tunneling length. Therefore, it is a local model.

The recombination-generation rate is given by

$$G_{BBT}^{\mathrm{SCHENK}} = \mathrm{A.BBT.SCHENK} F^{7/2} S \left(\frac{(A^{\mp})^{-3/2} exp\left(\dfrac{A^{\mp}}{F}\right)}{exp\dfrac{(\mathrm{HW.BBT.SCHENK})}{kT} - 1} + \frac{(A^{\pm})^{-3/2} exp\left(\dfrac{A^{\pm}}{F}\right)}{1 - exp\dfrac{(-\mathrm{HW.BBT.SCHENK})}{kT}} \right) \tag{3-438}$$